# Parallel transport of long mean-free-path plasma on open magnetic field lines

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Plasma transport on open magnetic fields that intercept the chamber wall or divertor plates can be dominated by the parallel particle and energy transport. The parallel transport theory becomes especially challenging and interesting when the mean-free-path (*mfp*) of the plasma becomes comparable to or greater than the field line connection length over which there is significant $|B|$ modulation. This regime of high temperature but low density is opposite to the usual low temperature experiment outside magnetic confinement fusion. It can be accessed, with the aid of a low recycling wall, by the axisymmetric scape-off-layer (SOL) plasma in all toroidal and linear devices, or a non-axisymmetric plasma on open field lines produced by either an externally introduced resonant magnetic perturbation or MHD instabilities during a tokamak major disruption.

The collisionless or nearly collisionless parallel transport theory on open field lines is different from the conventional collisional theory, which is based on the solution of the Braginskii equations, in that the plasma must be modeled with anisotropic temperatures and the collisional closure of parallel heat flux does not apply. The physics description must be beyond the double-adiabatic model in that heat flux must be retained in the energy equations. Here we present such a theory building upon the fluid moment equations of the kinetic equation in the leading order of $\rho/L$. The different and dominating roles of $|B|$ modulation and the two components of the parallel heat flux (one associated with the parallel thermal energy $q_n$ and other associated with the perpendicular thermal energy $q_s$), in determining the plasma profiles (density, parallel temperature, perpendicular temperature, ambipolar potential, and plasma parallel flow), are elucidated by general analytical expressions and confirmed by first-principles kinetic simulations in a linear geometry of open magnetic field lines with significant flux expansion toward an absorbing wall.

It is also found that the parallel heat flux, which must be calculated from kinetic theory in the long *mfp* regime, can have surprising behaviors along an open field line with significant field strength modulation. A remarkable finding is that the parallel heat flux $q_n$ can run against the parallel temperature gradient when there is significant flux expansion toward the wall. This is analytically demonstrated by solving for the parallel heat flux from the kinetic equation with an upstream source, and numerically verified with aforementioned kinetic simulations.

The implications of our long *mfp* parallel transport theory and the physics findings will also be explored in the context of tokamak divertor optimization and numerical modeling of a tokamak SOL plasma. This work was supported by the Department of Energy Office of Fusion Energy Sciences.